

**DEVELOPMENT OF FLIGHT TECHNOLOGY FOR FUTURE LASER-COOLED SPACE CLOCKS**

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We report on the development of flight technology to be used in future space-based, laser-cooled atomic clocks. The core technologies for these and future LCAP missions are being developed at the Jet Propulsion Laboratory, with the current emphasis on developing high-risk components such as the laser and optics subsystem, and non-magnetic ultra-high-vacuum-compatible mechanical shutters. The shutters will be used for light baffling and possibly some velocity selection for the slow atomic beam at the heart of these clocks. Prototype shutters are being manufactured currently. Results of performance tests will be presented.

Significant technical challenges in developing a laser cooling apparatus for space applications include reducing the volume, mass, and power requirements, while increasing the ruggedness and reliability in order to withstand typical launch conditions and achieve several months of unattended operation.

The micro-gravity environment offers significant advantages to a variety of high precision laser-cooling experiments for which interaction times are limited primarily by gravitational effects on Earth. Two flight definition experiments to develop space-based atomic clocks have recently been funded by the Microgravity Research Division of NASA as a part of its Laser Cooling and Atomic Physics (LCAP) program. The first of the missions, the Primary Atomic Reference Clock in Space (PARCS), has principle investigators at the National Institute of Standards and Technology and the University of Colorado, and is scheduled to fly aboard the International Space Station (ISS) in 2004. The second, the Rubidium Atomic Clock Experiment (RACE), has its principle investigator at Yale University, and is scheduled to fly in 2006. Experiments must also be adapted to the constraints of the various science platforms available on the ISS.

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# Flight Project Collaborators

## PARCS

### U. Colorado:

Neil Ashby (PI)

### Harvard-Smithsonian

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### Politecnico de Torino

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### JPL:

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## RACE

### Yale:

Kurt Gibble (PI)

Chad Fertig

### JPL:

W. M. Klipstein

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# Outline

- Overview of NASA's LCAP program
- Description of NASA's laser cooled space clock missions
- Flight technologies for space clocks
- The JEM-EF platform

# Laser Cooling and Atomic Physics

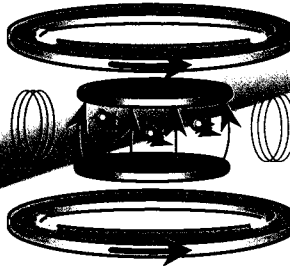
*Using the space environment to investigate ...*

## Laser-Cooled Atomic Clocks



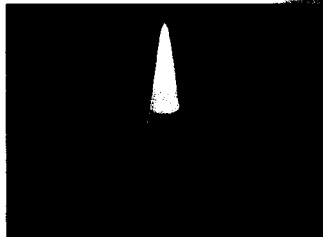
... if all clocks keep the same time or if our description of nature's forces is incomplete.

## Permanent Electric-Dipole Moment



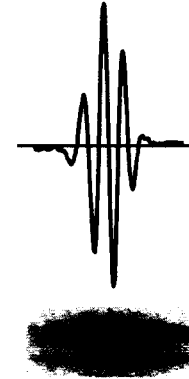
... if the electron has a dipole moment. Depending on the value, the standard model of particles and fields may have to be modified.

## Bose-Einstein Condensation



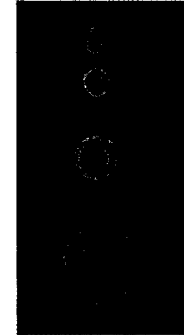
... if an enhanced understanding of atomic interactions can be achieved in space.

## Matter Wave Gyro



... if space can be used to establish stringent bounds on fundamental laws and forces of nature

## Atom Laser



... if we can build improved atom lasers in microgravity.

2000

2015

Future

## State of the NASA Program

### Ground Investigators

|               |        |                     |                           |
|---------------|--------|---------------------|---------------------------|
| D. Heinzen    | 94NRA  | EDM                 | University of Texas       |
| R. Hulet      | 94 NRA | Cooled Li           | Rice University           |
| W. Nagourney  | 94 NRA | Ion Clock           | University of Washington  |
| K. Gibble     | 94NRA  | Rb Atom Clock       | Yale University           |
|               |        |                     |                           |
| R. Hulet      | 96 NRA | BEC in Li           | Rice University           |
| M. Kasevich   | 96NRA  | Atom Interferometry | Yale University           |
| W. Phillips   | 96NRA  | BEC                 | NIST-Gaithersburg         |
| W. Ketterle   | 96NRA  | BEC                 | MIT                       |
| J. Ho         | 96NRA  | BEC-Theory          | Ohio State University     |
| J. Javanainen | 96NRA  | BEC-Theory          | University of Connecticut |
| J. Hall       | 96NRA  | FP tests w/clocks   | University of Colorado    |
| R. Walsworth  | 96NRA  | Cryo hydrogen maser | SAO                       |

### Flight Investigators

|             |        |          |                 |
|-------------|--------|----------|-----------------|
| K. Gibble   | 96NRA  | Rb Clock | Yale University |
| D. Sullivan | 96 NRA | Cs Clock | NIST-Boulder    |

# Overview of LCAP Flight Projects

## **PARCS (Primary Atomic Reference Clock in Space)**

**Principle Investigators:** D. Sullivan (NIST), N. Ashby (U. Colo.)

Development of a laser cooled **Cesium** clock for the realization of the unit of time, to operate continuously for at least 90 days. Use of orbiting clock for relativity experiments and global precise frequency distribution.

## **RACE (Rubidium Atomic Clock Experiment)**

**Principle Investigator:** K. Gibble (Yale)

Development of a laser cooled **Rubidium** clock for ultrahigh accuracy (exceeding a part in  $10^{16}$ ), to operate continuously for at least 90 days. Use of clock for relativity experiments and cold collision studies.

# *NASA and Clocks*

Present and Past:

- Spacecraft navigation
- Radio Science
- Gravity Probe A

Future:

- Laser Cooled Atomic Space Clocks
- Super-Conducting Microwave Oscillator
- Autonomous Spacecraft
- “GPS-like” navigation systems supporting Mars exploration.

# Current Status

PARCS and RACE are currently in their definition phase, in which the scientific goals of the missions, and the requirements of the instruments to meet those goals are being generated and refined.

- Choice of platform
- Mission parameters
- Choice of technologies (local oscillator, time transfer)
- Identification of technical hurdles

PARCS will move into the design/build phase in the fall of this year. RACE is expected to follow in spring '02. We are targeting a Dec. '04 launch for PARCS, with RACE following 16 months later.

# Physics with Clocks in Microgravity

## Tests of General Relativity:

- Gravitational frequency shift
- Local position invariance
- Anisotropy of  $c$  (Kennedy-Thorndike experiment)



## Technical measurements

- Improved realization of second
- International time coordination
- Study of GPS satellite signals



# The PARCS instrument

- Cesium atomic clock, employing optical molasses to collect cold atoms. Multiple ‘balls’ of atoms will be launched so as to obtain high stabilities while minimizing the spin-exchange frequency shift.

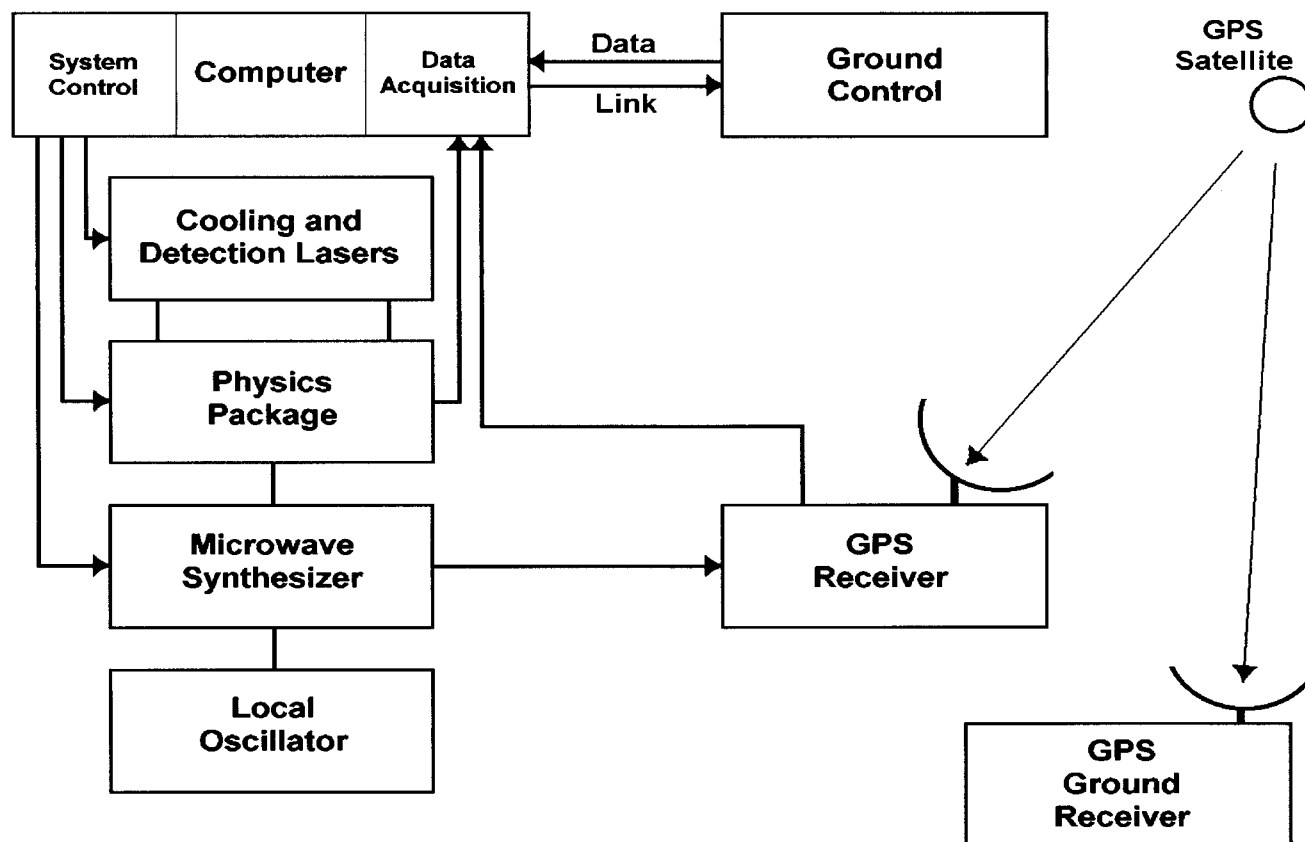
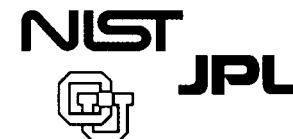
Accuracy goal of  $1 \times 10^{-16}$ .

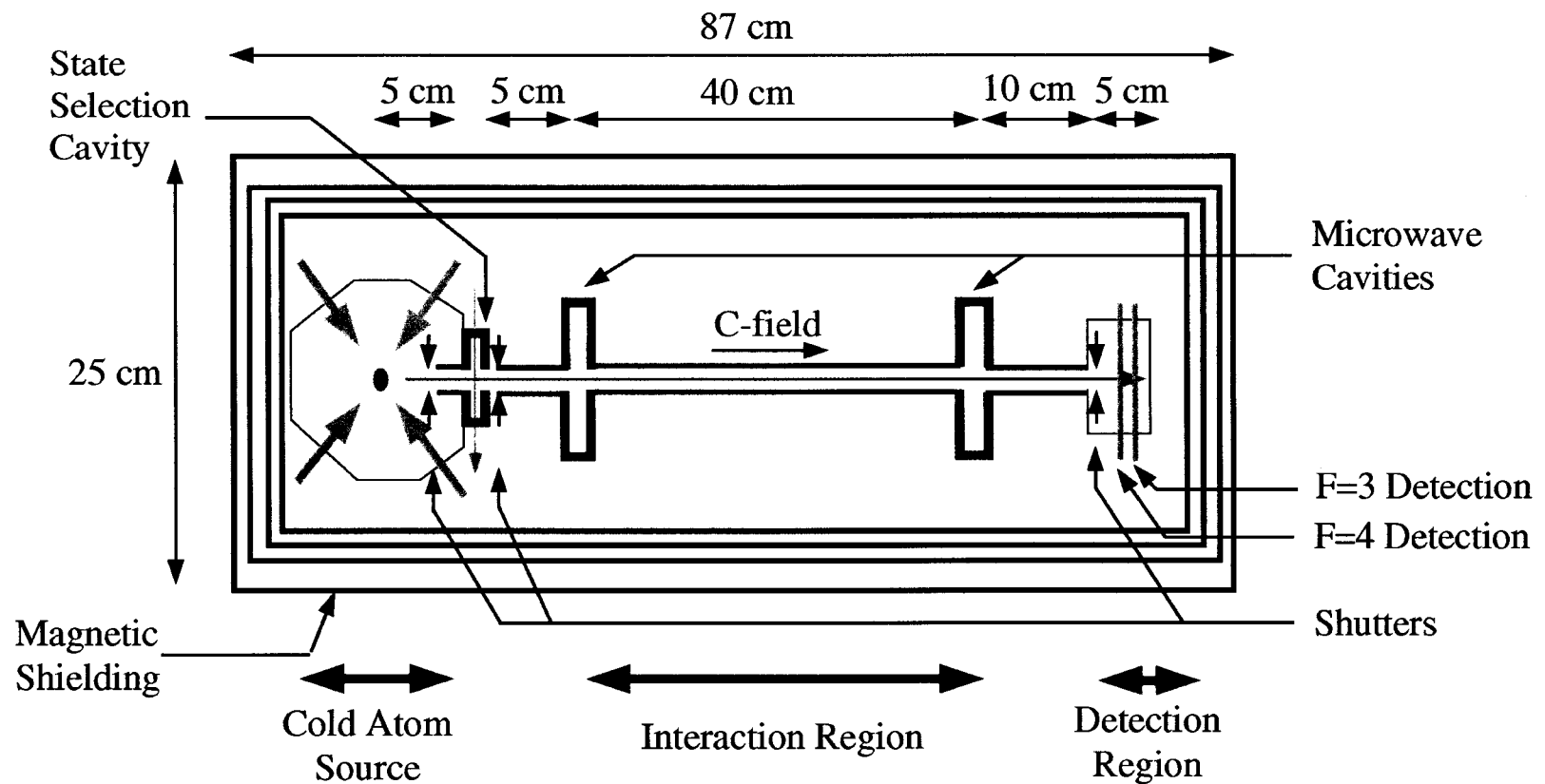
- The Local Oscillator will be a space qualified Hydrogen maser built by Harvard Smithsonian Center for Astrophysics (SAO). This device has a short-term stability better than  $\sigma_y(\tau)=5 \times 10^{-14}\tau^{-1/2}$ .

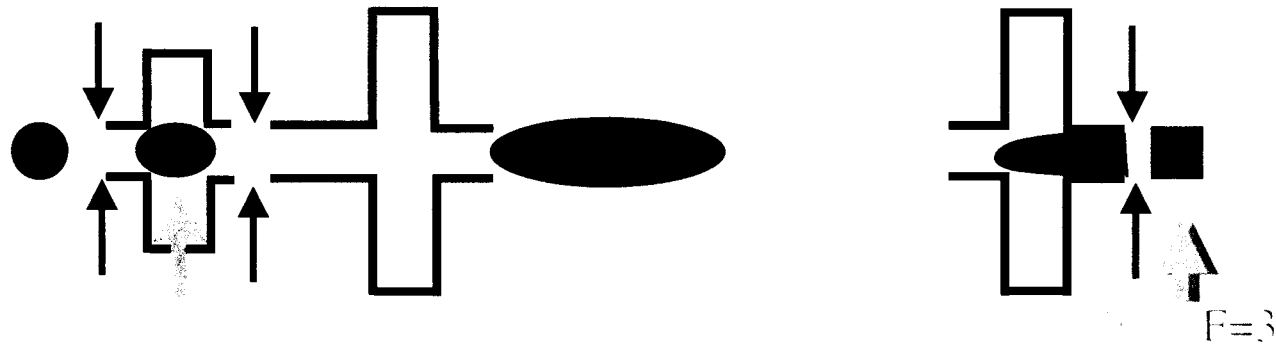
- GPS carrier-phase measurements will be utilized for both time transfer and precise determination of the ISS orbit and velocity.

**PARCS**

# Block Diagram of Experiment







**Collect:**  $N_0 = 1 \times 10^7$  cold atoms/ball

**Launch:**  $N_{m=0} = 10^6$  in  $m = 0$  at 2 Hz

**Detect:**  $N_D = 2500$

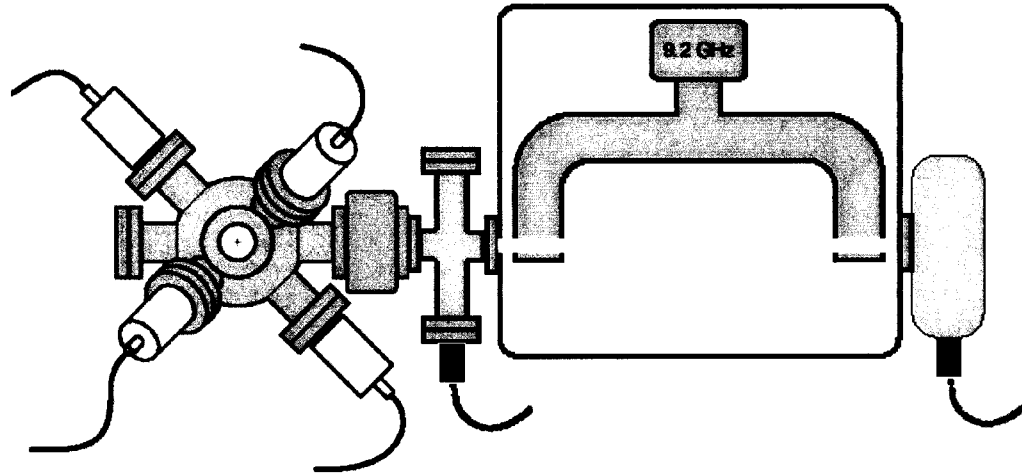
**Ramsey time:**  $T_R = 5$  s



**Source “brightness” achieved so far:**

- $N_0 \sim 2 \times 10^8$  (in 1 s) in vapor cell molasses (Ch. Salomon, Paris)
- $N_0 \sim 2 \times 10^7$  (in .5 s) in PARCS testbed at NIST

# Space Clock Challenges



## Laser Cooled Atom Source

- Lasers
- Optical frequency control
- Optical fibers
- Fluorescence detection
- Vacuum chamber
- Computer control
- Electronics
- Magnetic field control
- Cesium atom source

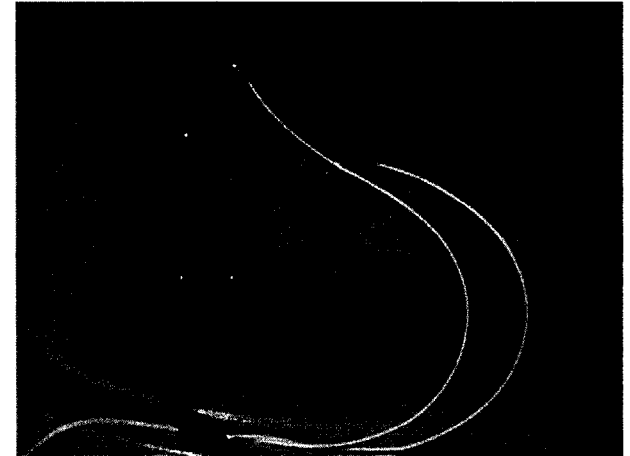
## Clock Package

- Microwave electronics
- Local oscillator
- Synthesizer
- Cavity
- More magnetic field control
- Thermal control
- Light baffling/shutters
- Vacuum requirements
- Measurement system

# The PARCS Laser System

## Baseline design

- Extended cavity master laser (linewidth  $\sim 500$  kHz)
- Injection-locked slave lasers ( $2 \times 200$  mW)
- Acousto-optical modulators for frequency control
- Polarizing Optical fibers for beam delivery



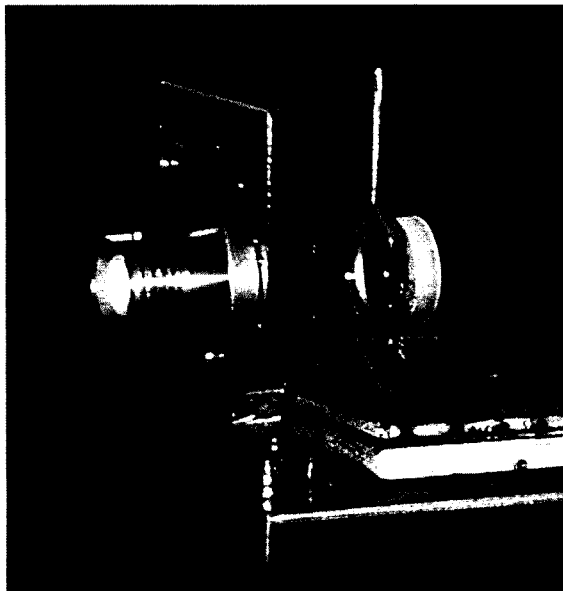
New Focus Vortex laser on JPL shake table

## Vibration testing

We have vibration tested a variety of components for the PARCS optical system, including an extended cavity laser, acousto-optic modulators, optical isolators and mounts. Each component survived to the levels required for a shuttle launch.

## Optics mounting

We are investigating the use of laser welding techniques to rigidly mount optical components



Lens mounted with laser welding

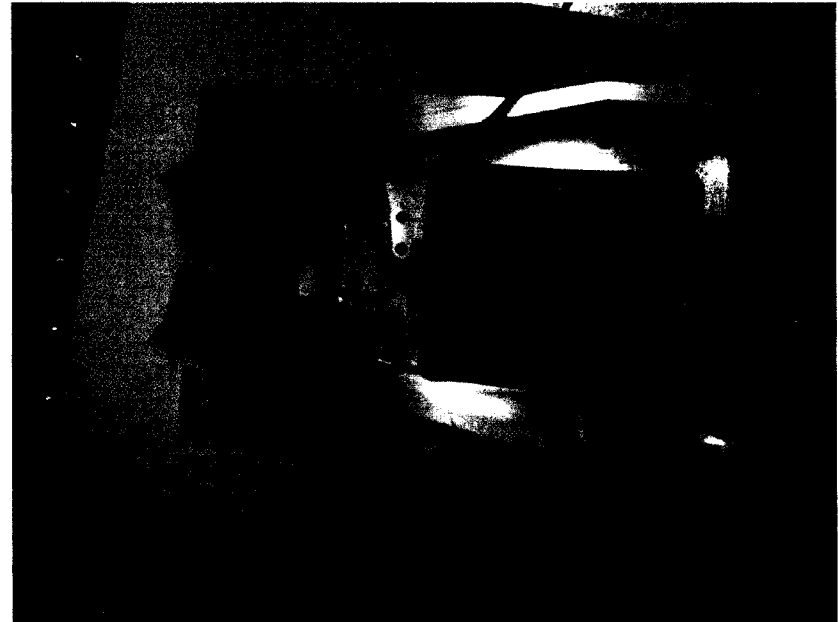
# Non-Magnetic Shutter

High performance shutters are required by both RACE and PARCS to achieve optimal performance.

Requirements include:

- High reliability (1 year operation at 10Hz w/o failure)
- Fast ( $< 1$  ms time from 100% closed to 90% open)
- Non-magnetic ( $< 1\text{-}2\ \mu\text{G}$  stray field at 1cm)
- Ultra-high vacuum compatible ( $< 10^{-12}$  atm)
- Relatively large aperture ( $> 1$  cm)
- Cannot disturb microgravity environment.

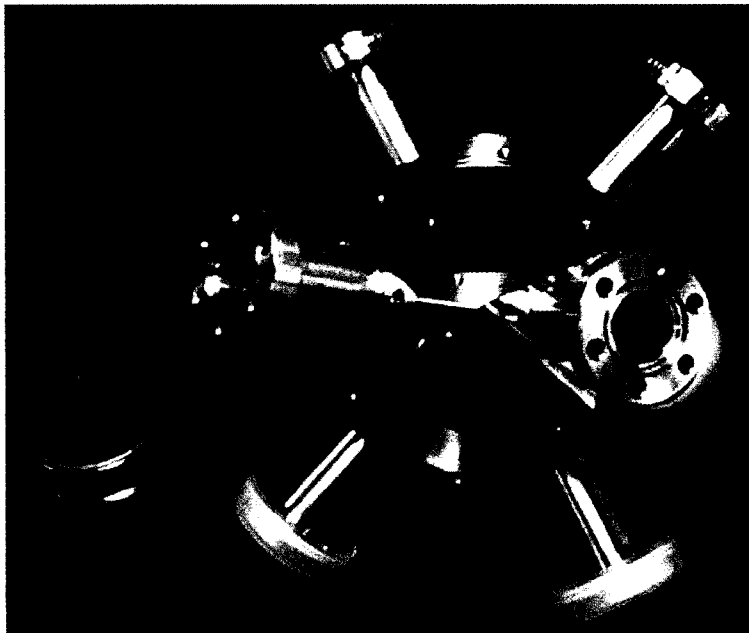
The Detection region shutter will operate at a 10 Hz rate, with a 90% open duty cycle.



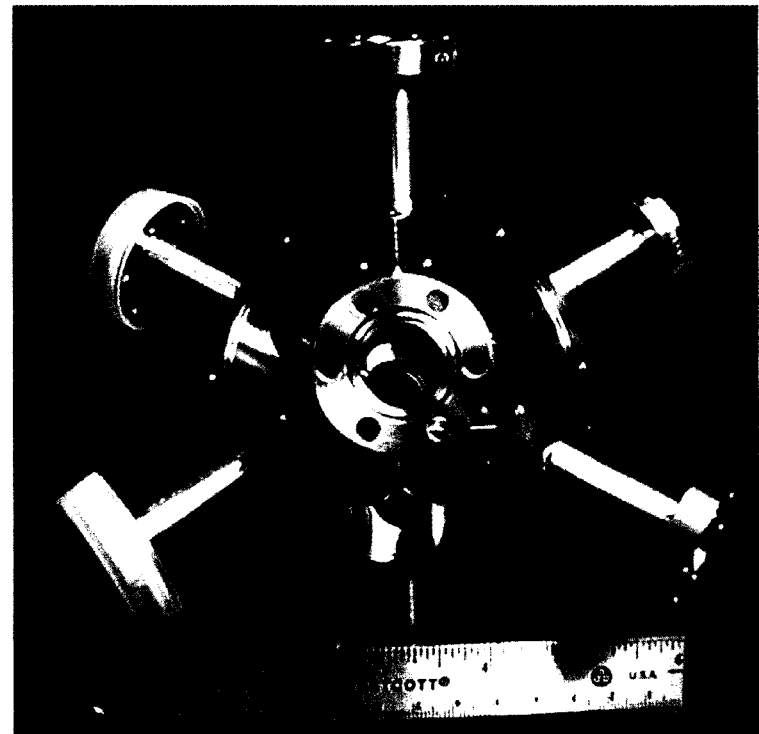
Recently constructed prototype of PARCS/RACE shutter. Device is built using commercial PZT actuators and non-magnetic materials.

# Titanium Source Chamber

Chamber has 6 large ports with welded re-entrant windows for collection beams. 8 changeable smaller ports are used for beam extraction, the cesium source, fluorescence monitoring, and pump-out. Titanium is lighter, than stainless steel, less magnetic, and does not source hydrogen.

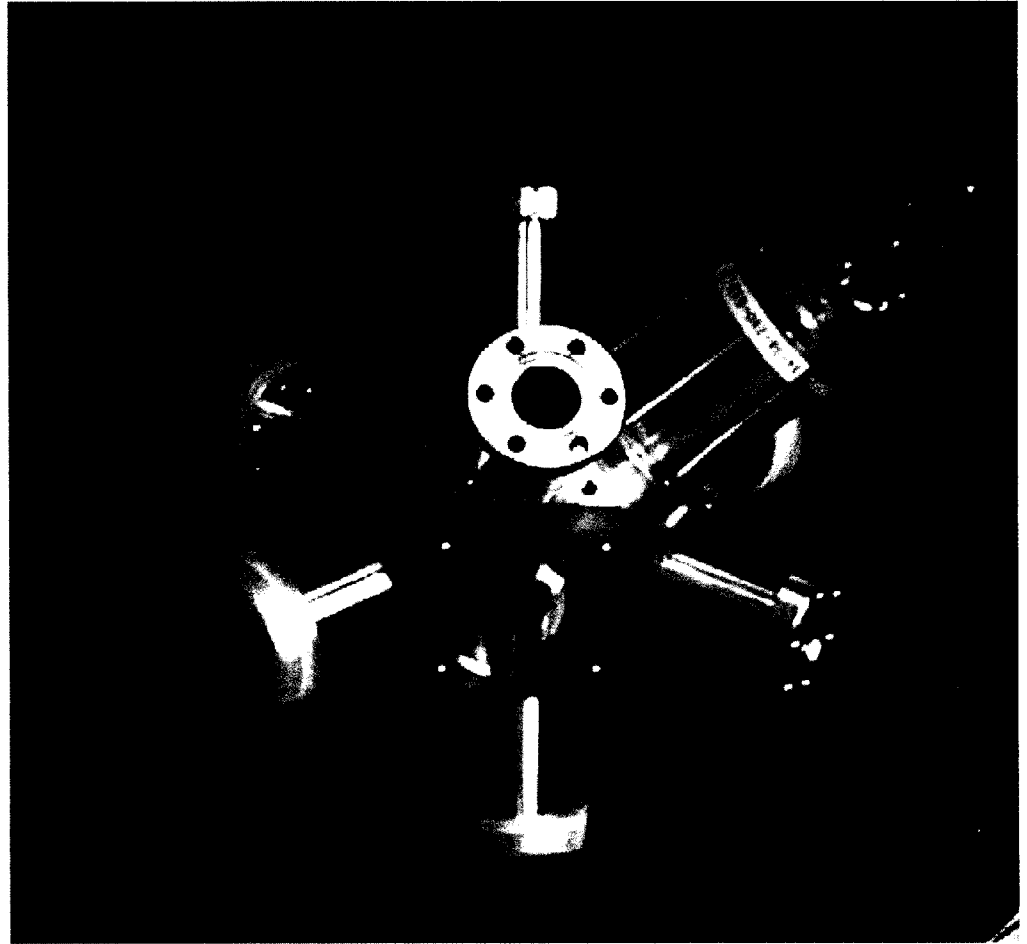
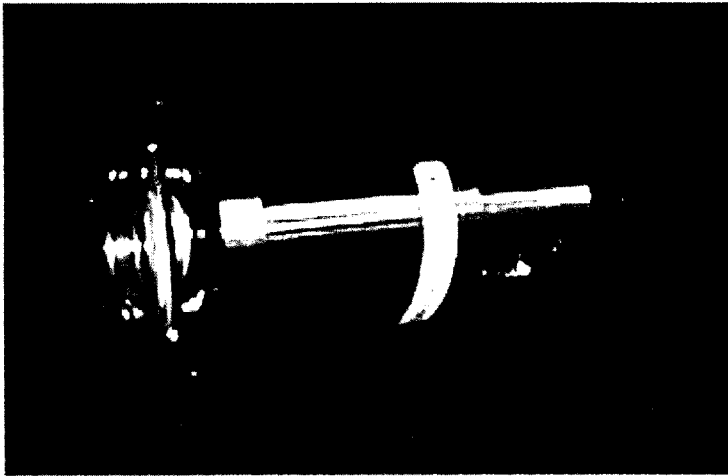


Chamber showing one window on weldable sleeve.



Chamber in launch configuration

# Fiber-Coupled Collimators



6 fibers bring the trapping and cooling light from the laser package to the physics package. Fiber-coupled collimators bolt to the collection chamber.

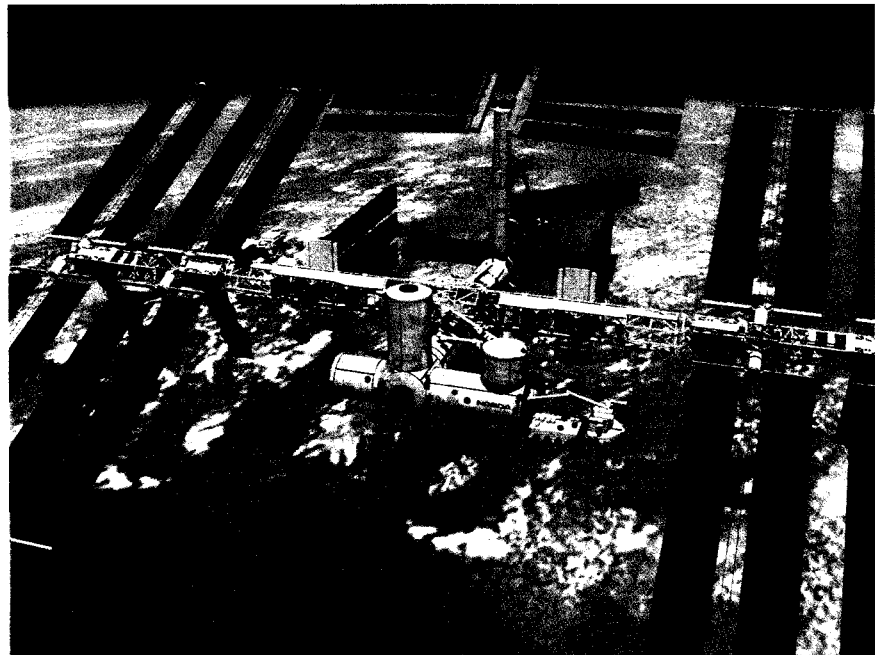
# PARCS Time Transfer

## Requirements to meet science objectives

- 100 ps time transfer stability
  - Position and velocity determination:  $\Delta x < 10$  cm,  $\Delta v < 1$  cm/s
- ⇒ Use **GPS carrier phase technique**

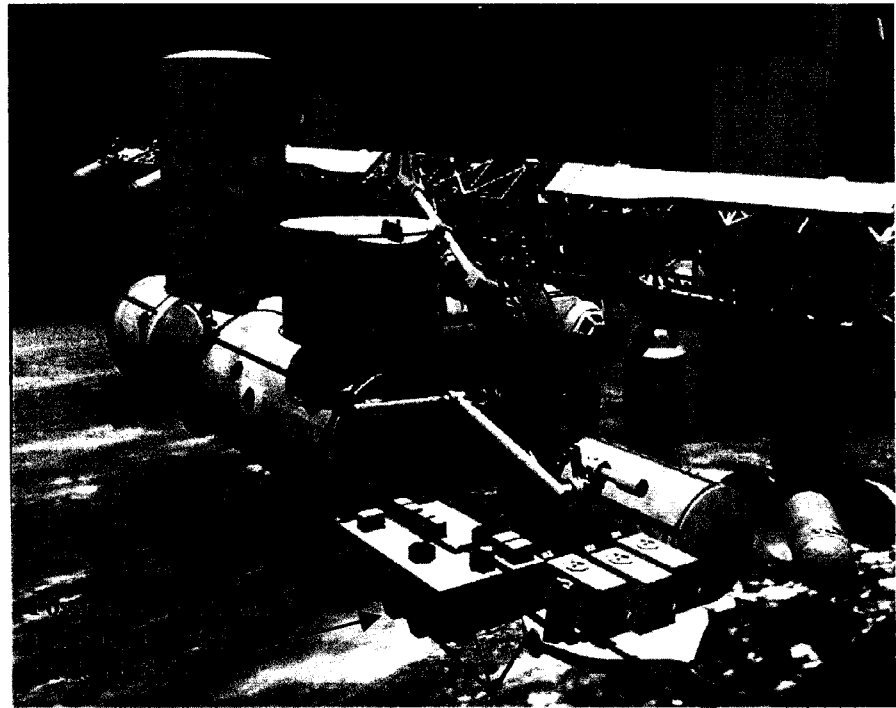
## Technical issues

- Need external antennae
- High quality rf link
- Multipath interference
- Visibility of GPS satellites



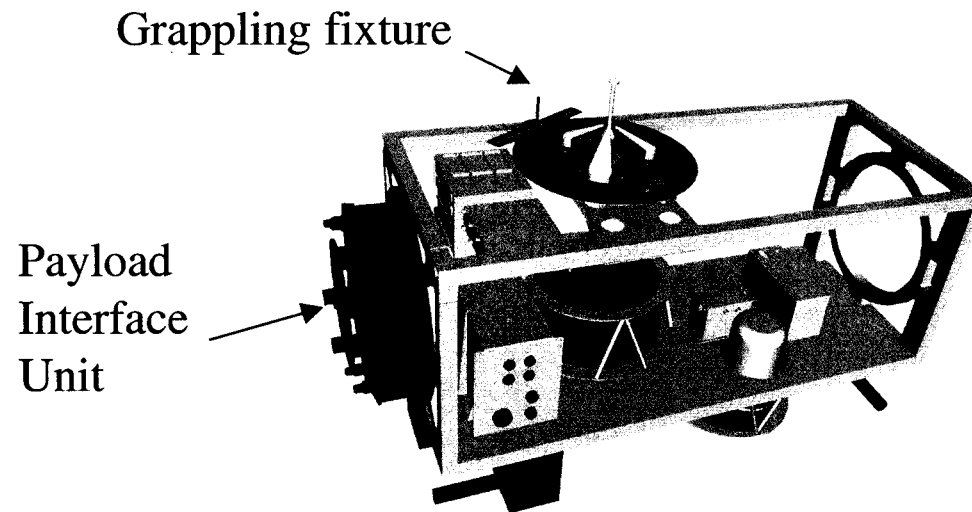
## JEM external facility:

- Exposed “porch” attached to Japanese Experimental Module (JEM) with slots for ten payloads
- Vibration environment measured, but no vibration isolation provided
- Possible proximity to the superconducting Microwave Oscillator (SUMO)
- Both zenith and nadir pointing instruments can be located on the same payload

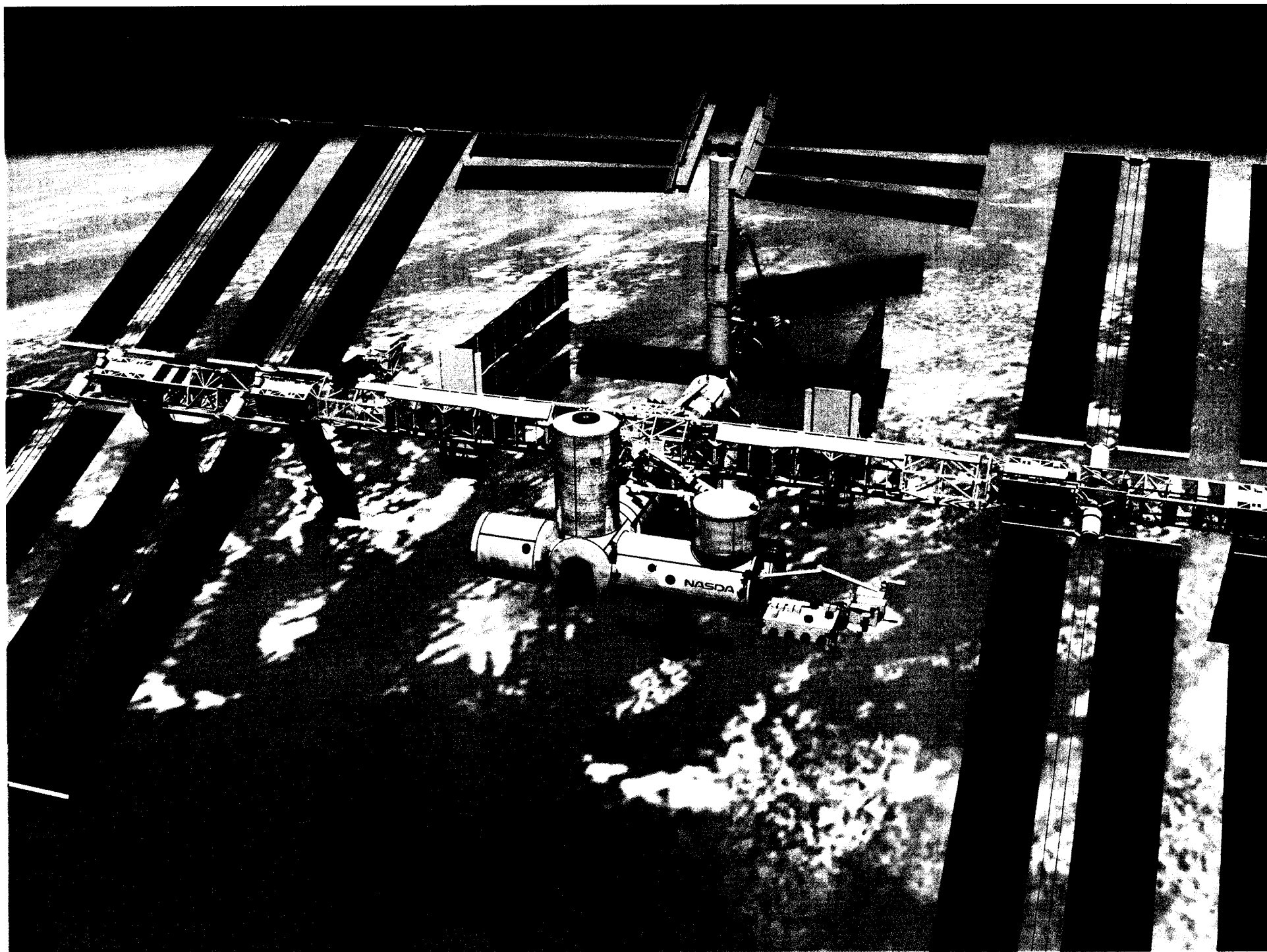


JEM-external facility. Shown with no payloads attached.

# The JEM-EF payload bus



- 3 kW power available (120 Vdc)
- $1.8 \times 1.0 \times 0.8$  m volume
- mass up to 500 kg.
- 2 kW of closed-fluid cooling
- Ethernet, MIL STD 1553 data



**JPL**

# LCAP Timeline

